

# On strangelets in magnetosphere<sup>1</sup>

Haret C. Rosu <sup>2</sup>

IFUG, Apdo Postal E-143  
León, Gto, México

## Abstract

A short discussion is provided on the hypothesis of strange quark dust of low specific charge in the terrestrial magnetosphere. We suggest by means of rough estimates the possible existence of a strangelet belt in the magnetosphere.

PACS: xx.xx.Let1let2, xx.xx.Let1let2

## 1 Introduction

The dark matter (DM) is a central paradigm of modern astrophysics with cosmological implications. It is based on the observed flat rotation curves of galaxies. Various exotic DM candidates have been proposed in the literature. Among them, baryonic DM was not much favored theoretically in the past few years. However recent possible detection by MACHO [1] and EROS [2] collaborations using the microlensing scanning technique of Large Magelanic Cloud (LMC) resettled the interest in baryonic DM [3]. The statistics of microlensing events is rapidly increasing [4] and already an average mass of  $\approx 0.1M_{\odot}$  has been derived for the DM chunks. At the same time, the observed events might be ascribed to microlensing by stars within the LMC itself [5].

My aim in this paper is to discuss strange quark matter (SQM), a more exotic baryonic candidate for DM, in a space physics context, namely within the magnetosphere, updating a hypothesis that I made 8 years ago [6]. The essential speculation is the possible existence of a strangelet belt in the magnetosphere.

## 2 Strange Quark Matter

If we look strictly at the numerical value of the binding energy, the most stable matter form known so far is nuclear matter ( $\sim 15MeV/N$ ) and its clustered aspect- atomic nuclei ( $\sim 8MeV/N$ ). Quantum Chromodynamics (QCD), the nonabelian generalization of Quantum Electrodynamics (QED) has opened new horizons concerning metastable or even stable matter states at high energy densities ( $\geq 1GeV/fm^3$ ). As we all know, QCD asserts that the *atoms* of our world are the so-called quarks, a kind of nonabelian electrons living only within a limited volume of hadronic range ( $\sim 1 fm^3$ ). We stress that we do not know what quarks really are and all our speculations start by considering them just ordinary fermions with a more complicated internal symmetry. This fact might not be quite right. The chromophotons (i.e., the gauge fields of QCD) are known as gluons and live also in the compressed (perturbative) vacuum inside hadrons. This confinement property of QCD is one of the two most important features of this theory. It is not at all well understood at the present time. The other fundamental property, asymptotic freedom, enables someone to apply perturbative methods at very high energies. The arguments used to give reasons for confinement are topological ones

---

<sup>1</sup>astro-ph/9410028; ifug-22/94

<sup>2</sup>e-mail: rosu@ifug.ugto.mx

(e.g., the chromoelectric Meissner effect), but in our opinion these are only analogies. If the confinement property is questioned, considering it a function of some parameters (e.g., the energy) we enter the wonderful world of all kinds of quark matter forms, a great challenge for detailed studies. One of the most promising candidate in this scheme is precisely SQM, possessing a surplus of s quarks ( $q = -1/3 e$ ) over the ordinary quark matter. It was Witten [7], back in 1984, who claimed that the s quark surplus comes from assuming the Fermi momentum of the quark matter to be about 300 MeV, more than the mass of that quark ( $\sim 200 \text{ MeV}$ ) and thus allowing a part of the up and down quarks to become spontaneously strange quarks. In this way the Fermi momentum is lowered and so is the energy. A massless quark flavor taken as a Fermi gas exerts a pressure  $p_F^4/4\pi^2$ , where  $p_F$  is the Fermi momentum. For quark matter without strangeness, charge neutrality implies a chemical potential  $2^{1/3}\mu$  for the d quarks, where  $\mu$  is the chemical potential for the u quarks. Thus the total pressure would be  $(1 + 2^{4/3})\mu^4/4\pi^2$ . In the case of 3 flavors and zero mass for s quarks, the same pressure is exerted at a lower Fermi momentum,  $\mu_3 = [1/3(1 + 2^{4/3})]^{1/4}\mu$ . When we compare this with the Fermi momentum of a two flavor (u,d) quark matter,  $\mu_2 = [1/3(1 + 2^{4/3})]\mu$ , we get a figure smaller than unity,  $\mu_3/\mu_2 = 0.89$ . One can see that a parameter window opens up for the possible existence of three flavored quark matter. To go to more flavors is already not allowed, since the subsequent c,b,t quarks are too heavy and only unstable matter forms can be generated. The above Witten's estimates on the existence of SQM have been taken seriously by various authors. De Rujula [8] and De Rujula and Glashow [9] speculated that forms of SQM may populate the huge nuclear desert of 54 orders of magnitude in mass spectrum (and dimensions) lying between atomic nuclei and neutron stars. Alcock and Farhi [10] have shown that only lumps with baryon number larger than  $10^{52}$  (planetary masses) could survive with decreasing temperature of the Universe, close to the average mass of DM chunks derived by microlensing. Moreover, the astrophysical origin of SQM was investigated, for example Cyg X-3 can be an astrophysical source [11]. Strangeness affecting the inner core of neutron stars is a well-known conjecture [12]. Of course, one should imagine physical processes by which SQM is reaching the crust of neutron stars, and even raised to the pulsar magnetosphere giving signals to our antennas. An interesting argument is that SQM forms from atomic up to meteoritical dimensions might propagate in the astrophysical space over large distances, only slightly affected by the galactic magnetic field, due to its quasi-neutrality. So, even astrophysical SQM can be found in Solar System and in the very neighborhood of our planet. We recall that in 1979, Bjorken and McLerran [13] studied the hypothesis that Centauro cosmic ray events are initiated by explosive quark matter, and in the same year, Chin and Kerman [14] made an analysis of a class of strange quark droplets using the MIT bag model of hadrons.

Witten [7] gave the following estimate for the free SQM in our galaxy. Since the neutron stars are about 1 % of the star population of a galaxy, this means some  $10^9 - 10^{10}$  neutron stars in our Milky Way. Free QSM may be produced astrophysically in the collisions of neutron stars (very rare events) and in the gravitational disintegration of binary neutron star systems ( $10^6 M_\odot$  in our galaxy). With  $10^{-1} M_\odot$  ejected from such binary systems, there might be  $10^5 M_\odot$  of free SQM in our galaxy.

Farhi and Jaffe [15] provided the most detailed analysis of the properties of SQM. They used a Fermi gas model with  $O(\alpha_c)$  corrections and a bag model in the region of low baryon number (near the nuclear limit). The investigated baryon number spectrum ranged from  $10^2$  up to  $10^7$  and the main parameters were  $m_s$ ,  $\alpha_c$ , and  $B$ , the strange quark mass, the QCD coupling constant, and the vacuum energy density shift, respectively. Beginning with the PANIC talk of De Rujula [8] the notion of nuclearites, i.e., strange quark balls, started circulating.

### 3 Nuclearites in the magnetosphere

In his 1984 PANIC talk, De Rujula [8] gave some useful estimates concerning the nuclearites. Rujula supposed that nuclearites are major components of the local DM the Earth is passing through. They have to interact with matter by atomic collisions and there is energy loss. From this loss, the range of nuclearites as a function of their mass can be obtained. De Rujula found that nuclearites smaller than  $410^{-14}$  grams cannot penetrate the atmosphere, since they have very small ranges, and therefore at the sea level one can see them only indirectly through their secondaries. For a direct detection one may think of the magnetospheric environment. Before discussing this, let us recall that nuclearites have been classified in two types [15], [16]. Those ones with  $A \leq 10^6 \text{ amu} = 10^{-18} \text{ grams}$  are much akin to atoms, with clouds of electrons (as many as several hundreds) around, neutralizing the charge, which because of strangeness is only  $Z = 6A^{1/3}$  instead of

the usual  $Z \sim A/2$  for atomic nuclei. This type of nuclearites going down to the nuclear limit ( $10^{-22}$  grams) are called strangelets. As an example, a strangelet of  $10^{-18}$  grams has 600 electrons around and is 100 fm in size. The larger nuclearites are not very different from metallic ordinary matter, with the electrons inside them as a degenerate Fermi gas. One can consider even meteoritic scales as long as nothing is known on their mass distribution. In the following we shall concentrate on strangelets as fitting better a magnetospheric context. As we said strangelets can travel easily over large astrophysical distances. However strong magnetic fields of magnetospheric type can capture them, in view of the ionizing processes due to the particles of the radiation belts. The nuclearite motions in the magnetosphere can be studied as a simple application of the Störmer theory of the motion of charged particles in a dipole magnetic field. Here we sketch a short resume following the excellent review of Vallarta [17].

Take  $\rho$ ,  $\lambda$ , and  $\phi$  as spherical coordinates (radial distance, latitude, and longitude). The origin is chosen in the center of the Earth magnetic dipole. Positive  $\lambda$  means northern hemisphere, and positive  $\phi$  is westwards. A very useful change of variables was discovered by Störmer, through which all the physical quantities under consideration lose their dimensions:  $r = \rho/l_S$  and  $ds = v/l_S dt$ , where  $l_S$  is the Störmer parameter given by  $l_S = \sqrt{Mq/mv}$ , where  $M$  is the magnetic dipole moment,  $q/m$  is the specific charge of the particle, and  $v$ , its velocity.

In adimensional variables, magnetospheric movements of particles are written down as

$$r'' - r\lambda'^2 - r\phi'^2 \cos^2 \lambda = -\frac{\cos^2 \lambda}{r^2} \phi' \quad (1a)$$

$$r\lambda'' + 2r'\lambda' + r\phi'^2 \sin \lambda \cos \lambda = -\frac{2 \sin \lambda \cos \lambda}{r^2} \phi' \quad (1b)$$

$$\frac{1}{r \cos \lambda} (r^2 \phi' \cos^2 \lambda)' = \frac{2 \sin \lambda}{r^2} \lambda' + \frac{\cos \lambda}{r^3} r' \quad (1c)$$

Derivatives are taken with respect to  $s$ , the adimensional trajectory line element. To this system of equations, energy conservation must be added

$$r'^2 + r^2 \lambda'^2 + (r^2 \cos^2 \lambda) \phi'^2 = 1 \quad (2)$$

An immediate integration of Eq. (1c) gives

$$r^2 \phi' \cos^2 \lambda + \frac{1}{r} \cos^2 \lambda = \text{const} = 2\gamma_1 \quad (3)$$

where the constant of integration is another well known parameter in the Störmer problem, which physically has the meaning of the axial projection of the angular momentum on the dipole axis. Finally, one can easily obtain the celebrated equation

$$\pm \sin \theta = \frac{2\gamma_1}{r \cos \lambda} - \frac{\cos \lambda}{r^2} \quad (4)$$

where  $\theta$  is the angle between the trajectory direction and the meridian plane, and the  $\pm$  sign is the charge sign. The last equation gives us allowed and forbidden regions in the meridional plane corresponding to the simple condition  $|\sin \theta| \leq 1$ .

As is known an experimental confirmation of the old Störmer theory (1907) came only in 1958 after the first extraatmospheric flights, giving evidence on the existence of radiation belts [18]. In the physics of belts the McIlwain parameter  $L = R_E / \cos^2 \lambda$  is used. The inner belt (protons and a small number of heavy ions) lies at  $1.6 \leq L_1 \leq 2.1$ , while the second belt (mainly electrons) is to be found at  $3 \leq L_2 \leq 5$ .

The strangelets, if any, should have a stationary behavior close to that of heavy ions, only that they should be found at even lower  $L$  parameter than  $L_1$ . Since their specific charge can be quite low perhaps they lase along magnetic field lines in mirror movements similar to the ordinary belts. The astrophysical strangelets can reach the lower  $L$ s by radial diffusion from higher  $L$  shells.

One may ask about the SQM fluxes. Using Witten's estimates, I found  $\sim 100$  grams of astrophysical SQM in the Solar System and for a mass distribution with a strong peak at  $10^{-21}$  grams, this would mean only one Avogadro number of astrophysical SQM in the Solar System. At the Earth orbit the corresponding figure would be  $10^{-11}$  strgl/cm<sup>2</sup> s, quite disappointing as expected. The DM hypothesis ( $10^{-17}$  grams/cm<sup>2</sup> s, on the other hand, for the same mass distribution, allows for figures comparable with the experimental ones

for ordinary baryonic matter, i.e.,  $10^4$  protons/cm<sup>2</sup>s, and  $10^1$  alpha particles in the same units, within the inner belt.

One can also be interested in an optimal value for the  $L$  parameter (as a function of energy) at which strangelet intensity reaches a maximum. The estimation of this critical  $L$  is known in the case of protons and heavy ions [19]; for protons,  $L_{cr,p} = 6.75E^{-1/4}(MeV)$ , and for heavy ions,  $L_{cr,hi} \sim Z^{1/2}A^{-1/4}E^{-1/4}(MeV)$ . The same type of relationship might work for strangelets. I give the following estimate,  $L_{cr,strgl} \sim 0.48Z^{3/2}A^{-1/4}E^{-1/4}(MeV)$ .

## 4 Conclusions

A heuristic discussion of a possible belt in the magnetosphere made of strangelets of low specific charge, similar to the more common radiation belts has been given in this paper. Such a strangelet belt may be due to the local DM density, and a very small component to astrophysical sources. If taken seriously (indeed, the old result of Alcock and Farhi [10] is against our framework, as we are left with the astrophysical component only), more detailed investigations will be required. One can also go with this hypothesis to other accessible planetary magnetospheres, e.g., Jupiter one.

## References

- [1] C. Alcock et al., Nature **365**, 621 (1993)
- [2] E. Aubourg et al., Nature **365**, 623 (1993)
- [3] F. De Paolis et al., astro-ph/9410016.
- [4] A. Udalski et al., Acta Astron. **43**, 289 (1993)
- [5] K.C. Sahu, Nature **370**, 275 (1994)
- [6] H. Rosu, in *Topics in Astronomy, Astrophysics, and Space Sciences*, vol. II, pp. 56-62 (CIP Press, Bucharest, 1986); preprint A-13/March 1986, IFA-Magurele.
- [7] E. Witten, Phys. Rev. D **30**, 272 (1984)
- [8] A. De Rujula, Nucl. Phys. A **434**, 605 (1985)
- [9] A. De Rujula and S.L. Glashow, Nature **312**, 734 (1984)
- [10] C. Alcock and E. Farhi, preprint CTP 1256 (1985)
- [11] V. Barger et al., Eds, *Cyg X-3*, Wisconsin report (1985)
- [12] G. Baym and L.D. Pethick, Ann. Rev. Nucl. Sci. **25**, 27 (1975)
- [13] J.D. Bjorken and L.D. McLerran, Phys. Rev. D **20**, 2353 (1979)
- [14] S.A. Chin and A.K. Kerman, Phys. Rev. Lett. **43**, 1292 (1979)
- [15] E. Farhi and R.L. Jaffe, Phys. Rev. D **30**, 2379 (1984)
- [16] L.J. Boya et al., Phys. Rev. A **32**, 1299 (1985)
- [17] M. Vallarta, Hand. d. Physik, vol. XLVI/1, pp. 88-129 (1961)
- [18] J. van Allen and L.A. Frank, Nature **184**, 219 (1959)
- [19] M.I. Panasiuk, Kosmicheskie Issledovaniya **18**, 83 (1980)